Space Shingles

Casting bespoke connectors for structural shingles

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Abstract

The paper describes how established manufacturing methods and certified materials in metal casting are used in conjunction with 3D-printed moulds for creating geometrically complex structural aluminium connectors. To show the potential of this process we propose a novel connector that differs from bespoke tube connectors and traditional spider fittings. We showcase a connector for joining sheet material to form larger double-layered structural assemblies such as decks and shells without the need of any substructure.

The work lays out the digital process chain including design, engineering, and fabrication. This includes topology optimization of connectors towards structure, material use, and casting limitations. It describes the production of individually shaped connectors, which are produced indirectly using a large format binder-jet 3D-sand-printer for casting metal cores. It results in bespoke cast metal connectors with approved material properties. The work is situated between 3D-metal printing and 3D-printing sand moulds for bespoke metal casting.

A possible novel design application of such a plate connector is demonstrated in a shingled double-layered structure. It would allow for a loose-fit overlapping panel detail and thus eliminate elaborate flank machining. Such varying overlap between panels with relatively large tolerances also opens the possibility for constructing non-standard forms out of standard panels. It also allows to design with reused plates or production-waste material by employing combinatorial methods.

Keywords: 3D-printing, binder jetting, sand casting, metal joints, metal casting, digital fabrication, computational design, topology optimisation, reuse, upcycling.

Figure 1: Cast metal connector for space-shingles.

1 Introduction

1.1 Problem definition

Current methods for direct additive manufacturing metal such as direct metal laser sintering (DMLS), direct metal laser melting (DMLM), or 3D-printing with gas metal arc welding (GMAW) have hardly impacted architectural design and the construction industry. The only additive metal manufacturing process to have produced architectural results is wire arc additive manufacturing (WAAM). It delivered the first research projects and demonstrators at architectural scale. A significant contribution in that respect is the robotically printed MX3D Bridge engineered by Arup (2020).

A key project where architectural products were fabricated with DMLS is the tensegrity connector project also by Arup and presented by Ren and Galjaard (2015). The key benefit of a topologically optimised connector is that it is requiring only 25% of the material of a conventionally fabricated connector. Still, both processes have significant limitations to be used competitively in the ecosystem of today's construction industry. Parts fabricated with DMLS are relatively small and still way too expensive to justify the reduced material use. WAMM has delivered a demonstrator at architectural scale but still at a speed that is so far off from current production processes that it cannot be account as an alternative in the near future. Neither of these two methods is governed by current industry or building codes. They don't use standardised materials nor are their layer to layer biding characteristics fully controlled. Such material build-up can lead to anisotropic behaviour in the material of the finished part. A detailed overview of metal behaviour in additive manufacturing (AM) is described by Herzog et al. (2016).

As indicated above, AM in architecture is still challenged by the dimensions of building elements. A comprehensive overview of AM processes in construction is conducted by Paolini et al. (2019). The most promising projects addressing the scale problem in architectural AM are the ones that use a hybrid approach of small 3D-printed parts in conjunction with larger digitally fabricated components of standard materials such as beams, tubes, plate, panels or even formwork. A prominent example is the space-frame structure with 3D-printed connectors by Raspall et al. (2018).

Metal casting aluminium alloys by means of sand mould is a well-established process relying on tested methods and certified materials with known properties as laid out in DIN EN 1706 Aluminium und Aluminiumlegierungen (DIN 2020). Sand moulds for metal casting have been used for a few thousand years. The conventional processes for using sand mould in today industrial production are described in Manufacturing Processes for Design Professionals by Thompson (2007). Today, the process of 3D-printing sand moulds for casting metal parts is well established in industries such as automotive and machinery. Suppliers of 3D-printing machinery such as Voxeljet give an account of where their machinery is used in production (AG 2020). There is no significant difference in the performance of cast metal parts stemming from traditional sand mould or 3D-printed sand moulds.

Other than direct 3D-printing metal-casting requires a twofold forming process. Firstly, 3D-printing a sand mould with a binder jet printer and secondly, casting the form with molten metal. In addition, there is also some cleaning, and possible surface treatment to be done. There are some geometric limitations when using casting processes. Compared to direct 3D-printing these limitations are mainly in minimal cross-section dimensions. The moulds also require runner, riser and gating for the liquid metal to flow into the cavity and vent the remaining air. When taken out of the mould the metal parts have a rough finish and the tolerances of the process require further machining to have integrated features such as high-quality planar surfaces or threaded holes.

1.2 Knowledge gap

Complex architectural metal products such as spider fittings have been traditionally fabricated using processes such as investment casting or sand casting. Thompson (2007) compares these processes and their implication in Manufacturing Processes for Design Professionals. So far 3D-printed sand moulds are only experimentally used in the production of architectural metal products. A key project in that respect is Digital Metal: Shaping Liquid Pavilion by the ITA, ETH Zurich published for the CAADRIA conference by Meibodi et al. (2019). The project demonstrates the use of a 3D-printed sand mould to cast variable space-frame tube connectors. It provides a large degree of variation in the components and thus demonstrating the benefits and potential of 3D-printing the moulds rather than forming them traditionally.

In order for a process of 3D-printed sand moulds to be competitive within a generative design workflow, it is necessary to integrate the design of the moulds into the general workflow. Only then it is possible that geometric variation in the general layout of components propagates all the way down to the mould geometry. This process was explored in the Shaping Liquid Pavilion (Meibodi et al. 2019).

The project presented in this paper builds on that expertise. It goes further by exploring a new connector type which links plate elements directly and thus forming a structural and architectural surface without a supporting framing, see **fig. 1**. This unconventional structural system will be referred to as space-shingles. It has similarities to a spaceframe without the hierarchy between loadbearing and cladding elements.

The project aims to explore the architectural potential of cast metal parts from 3D-printed moulds as a connector for larger variable architectural assemblies where it provides the benefits of local geometric and structural adaptability. It also aims to advance the integration of post-casting machining for precise mechanical connections.

1.3 Objective

In order to show the potential for cast metal components with 3D-printed sand moulds, we propose a prototypical design for structural shingles namely space-shingles as shown in **fig. 2**. The idea of such a system is based on the notion of a space-frame but instead of linear members and connectors it proposed spatial connectors to link plates directly.

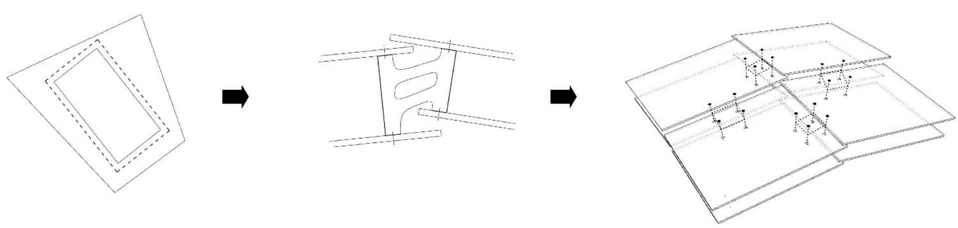

Figure 2: Schematic drawing of the space-shingle connector and lose fit plates.

We see this as a suitable test case for developing components which play an integral part in an architectural assembly. The connectors which link the shingles to a functional structure as well as providing architectural surfaces have a fair bit of geometric variation in order to reach the panels. They also offer the possibility to be topologically optimized for locally varying load cases.

Shingled structures in architecture have the advantage of taking up tolerances much better than any other system. They have been around for thousands of years. Modern interpretations of that strategy have even been proposed as cladding strategies for 300 m high-rise facades such as the Bishopsgate Tower by Hesselgren et al. (2007). On the other hand, the traditional use of shingled structures is still relevant in contemporary avant-garde architecture such as the Serpentine Pavilion Carpet of Stone by Ishigami (2020).

The loose-fit properties of shingled structures make them specifically suitable for novel recycling strategies in the context of computational design as they don't rely on "zero tolerance" and thus offer scope for combinatorial optimisation and form-finding strategies such as Mind the Scrap by Nolte (2020) or the paper Form Follow Availability by Brütting et al. (2019).

2 Methods

With the objective to evaluate the potential of cast metal components from 3D-printed moulds in architectural construction, we choose a path of design research. This involves geometric and physical prototyping, numerical analysis which all support the ideation process.

The work is conducted in a series of proof of concept prototypes. These will form the base for a full-scale architectural demonstrator at a later stage. The test context for this project is the concept of space-singles, which combines the precision of digital fabrication with the loose-fit of vernacular construction. Such a space-shingle structure could act structurally as a truss, shell or any hybrid in between as shown in **fig. 3**.

3 Proof of concept

3.1 Fabrication pipeline

Today, the production of structurally and topologically optimized metal connectors is mainly done where high numbers of parts are needed as in the automotive or aerospace industry. To realize such objects from drawings to physical artefacts several industrial fabrication processes are available. They are differentiated by

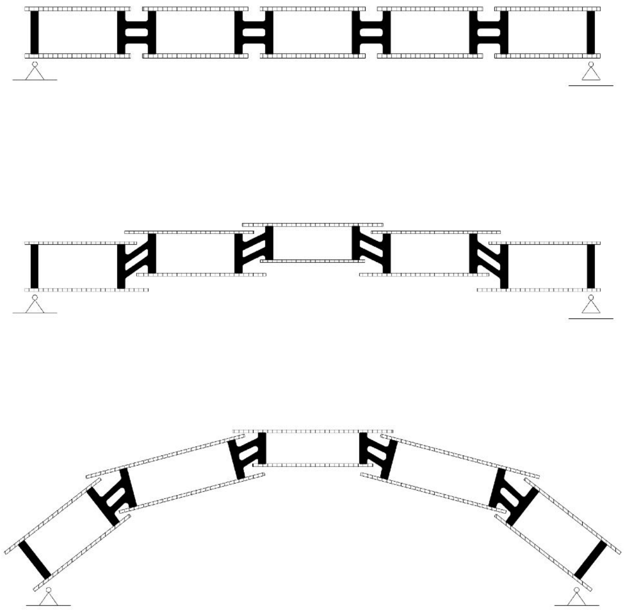

Figure 3: Different possible structural system of the space-shingle system form truss to shell.

DIN 8580 into cutting, assembling, forming. The available fabrication processes undergo continuous change along with technological development. Many of these processes and codes were developed when 2D paper drawings were the basis for any fabrication process.

Today 3D design-models can be evaluated for their structural performance almost in real-time and thus be topologically optimized for minimal material use. The realisation of such gradually changing objects is difficult to achieve with traditional cutting or assembling processes. Economic gains by reducing the amount of material might be eaten up by expensive fabrication processes required to realise such intricate structures.

A continuous process chain which links the digital 3D design-model to the final product without the above-mentioned limitations are casting and additive manufacturing methods. These processes have in common that formless matter is put into a fixed geometric shape. The initial material could be viscous, solid or gas-like.

The connector described in this paper is fabricated using two forming processes: 3D-printed moulds and metal casting. During the first step, a high-resolution sand mould is 3D-printed directly off the digital model. This is done on a Voxeljet VXC 800 with a continuous resolution of 400 dpi and a layer thickness of 0.2 mm. Such a printer with continues "endless" print-bed would allow for industrial production.

Key drivers for the development are obviously the fabrication constraints of the 3D-printing and metal casting process. The sand-moulds for the single prototypes were printed on a Voxeljet VX 200 (AG 2020) which has a maximum print bed of 300 x 200 x 150 millimetre. The prototyped connectors are around 140 x 140 x 140 millimetre in size.

After the binder has cured the mould are released from the printer. The half-moulds are properly cleaned of any loose sand. Therefore it is necessary to have each mould designed in two halves. These half-moulds also include a runner, riser, gating system for the liquid metal to flow easily and fittings to connect the two halves precisely together.

Once the two halves are joined the liquid aluminium alloy is cast into the mould. This forming process allows to fabricate complex and intricate parts to high precision. The casting process is shown in fig. 4. At the end of the life-cycle the used alloy can be molten again and is fully recycled without separating out any components.

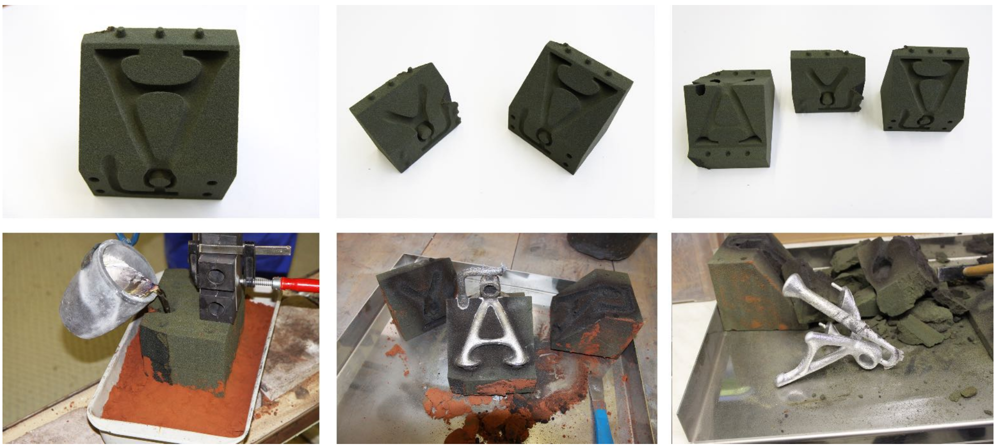

Figure 4: Casting process using a 3D-printed green sand mould.

3.2 Design pipeline

The overall geometry for the prototype was chosen to have a meaningful test context for connector-variation, structural conditions and difference in connection details. The shell-like structure exhibits enough curvature to be structurally significant (see fig. 5). It is still shallow enough the experience some moment forces which have to be taken up by the structural depth provided by the height of the connectors. The prototype consists of 144 panels, each around 800 x 800 mm and 10 mm thick, 60 connectors with an average height of 140 mm.

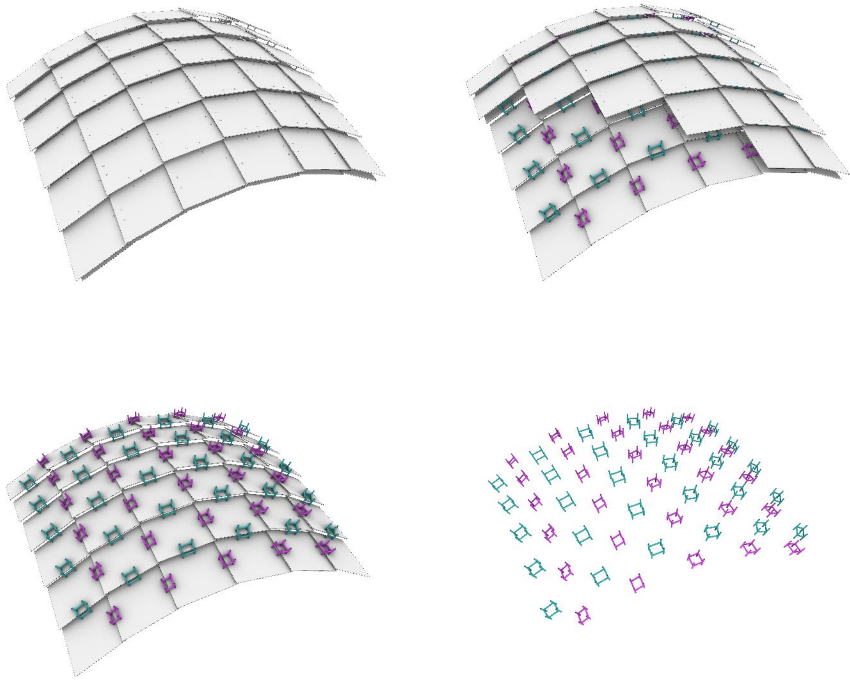

Figure 5: Space-Shingle structure. Double layered plates with connectors.

The model was defined as light weight parametric representation in Rhinoceros 3D Grasshopper consisting of planar quad surfaces and centre line geometry for the connector. The panels provide a tolerance zone which can take up 10% panel size while still providing enough overlap for the shingles to work as a rain-screen.

The local geometric range of connectors in terms of centre line length and angles form the base for developing the bounding volume topologically via a form optimisation process in Autodesk Fusion 360. The viability of the connectors contact surfaces to the panels was ensured, positions for threaded drill holes identified.

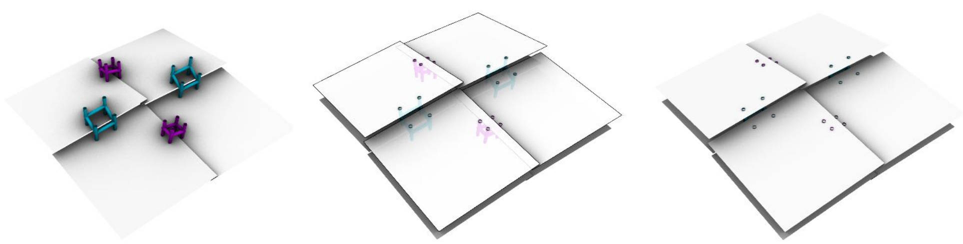

Figure 6: Connection logic of 8 structural space-shingles.

The two parted mould for each connector had to be generated in-line incorporating a system of runner, riser and gating to allow the liquid metal to fill all cavities. When the cast is finished, the sand mould is broken off and the excessive material cut off. The contact surfaces are machined for planarity and the threaded holed are cut at the mark points.

3.3 Engineering

The main principle of the proposed structural system is a spatial truss where the top and bottom chord are made up of plates linked by bending resistant connectors providing the necessary spacing for the required structural depth. The main feature of this structure is that top and bottom chord are made up of discontinuous parts, which is illustrated in **fig. 6**. The overall form is analysed under deadloads for displacement as shown in **fig. 7**. Based on the simulation the heights of the connectors are adapted where necessary to compensate over and under-performance. The load conditions at the connection points of each connector are taken into consideration for the topology optimisation.

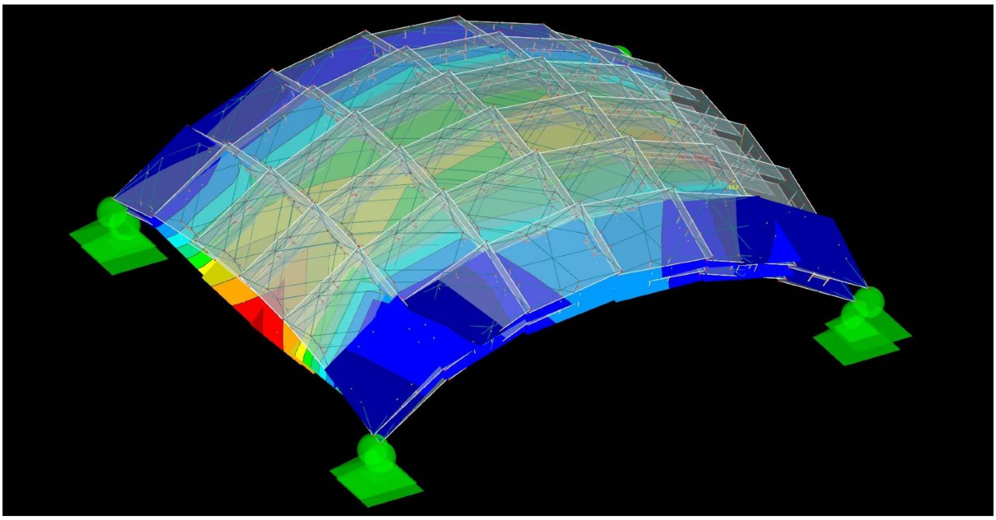

Figure 7: Displacement analysis under dead load. Span between supports 3800 mm/4400 mm.

3.4 Integrated design and optimisation

The design integration system was developed to control the overall geometry and provides the constraining information for developing the connector topology, namely the point fix locations as well as loading conditions at these points. This information was used to topologically optimize a base volume. Different initial volume geometries were tested as shown in **fig. 8**. The resulting connector topology is cleaned up geometrically and improved for 3D-printing and metal-casting constraints. The ideal form after casting and machining is shown in fig. 9.

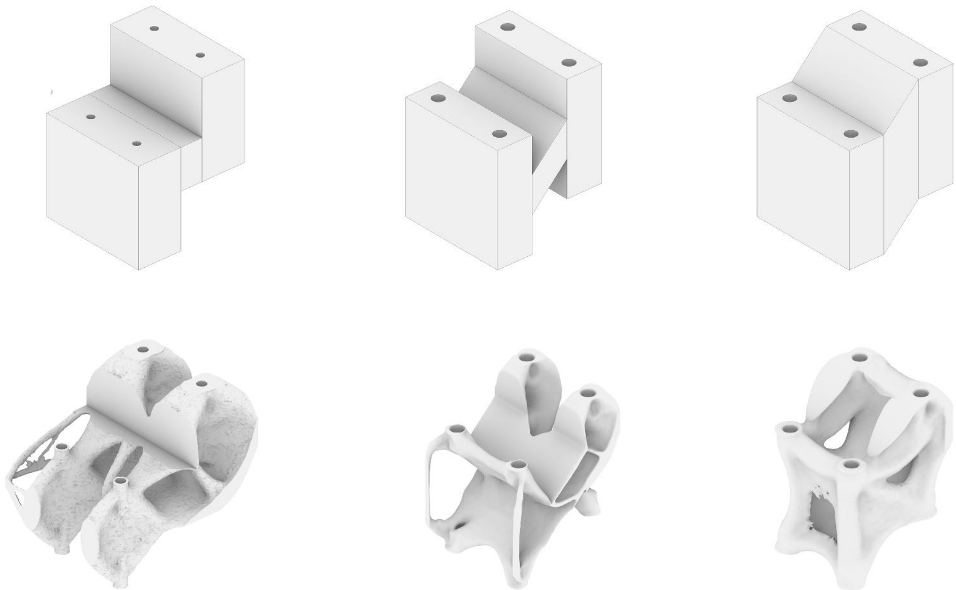

Figure 8: Topology study of connector based different bounding volumes.

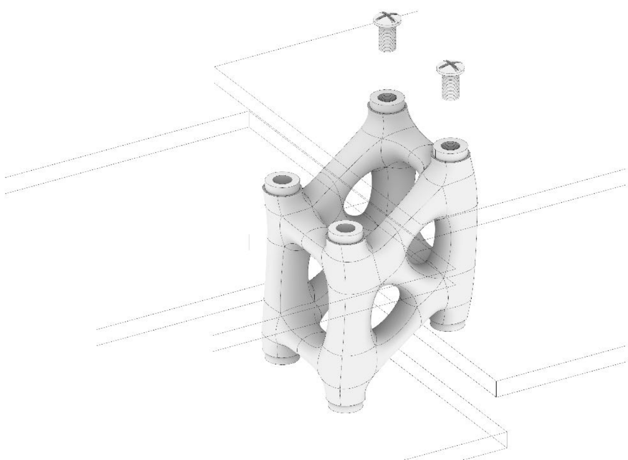

Figure 9: Connector prototype with plate-connection details.

4 Evaluation

Overall the system of space-shingles shows great potential to be further developed with such a bespoke metal cast connector. The connector itself, its geometric definition, the design integration as a digital model from design, optimization, fabrication also proved to work well. The fabrication process proved to fall into the tolerances as expected from a well-tested industrial process. Further destructive examination of the connector should be performed. These should be done in conjunction with thorough prototyping and design development of the connection detail between connector and plate.

5 Discussion

5.1 Outlook and impact of findings

The development so far seems very promising for feasible applications of metal cast connectors from 3D-printed sand moulds in an architectural context, see also **fig. 10**. The design of an overlapping loose-fit shingle takes out a significant degree of complexity in the manufacturing of the panels as it eliminates any plate-to-plate timber joint and allows for panel sizes tolerances in the margin of up to 10% in length.

Figure 10: Cast metal connector and space-shingles.

5.2 Further developments

The connection detail between metal connector and shingle plate should be further tested and developed. The design process should be further developed to harness the potential for material reuse and recycling. Scalability and process improvements for larger productions. All this would be best developed in the context of a larger architectural demonstrator. This would also address architectural questions such as integrating architectural elements, daylight and environmental performance, as well as human comfort. Along the way scaled prototypes such as shown in **fig. 11** could help to speed up the development cycles.

5.3 Possible products and applications

As metal casting is a well-established process and so is the fabrication of 3D-printed sand moulds, one can expect to bring such processes and products relatively fast to real projects in the building industry. The validation of structural performance can be done equally numerically as well as with physical testing. All the metal parts damaged in destructive testing or failing quality control can be recycled and fed back into the material flow. We hope to see novel products and hybrid systems maximising the potential of 3D-printed moulds for architectural metals casts connectors. We also see applications for processes which already consider 3D printing as a strategy but lack the high strength characteristic such as Digital Rubble Compression-Only Structures with Irregular Rock and 3D Printed Connectors by Wibranek and Tessmann (2019). It is up to designers and engineers to develop meaningful architectural products which go even beyond the potential of a highly variable, material minimizing, product presented in this paper.

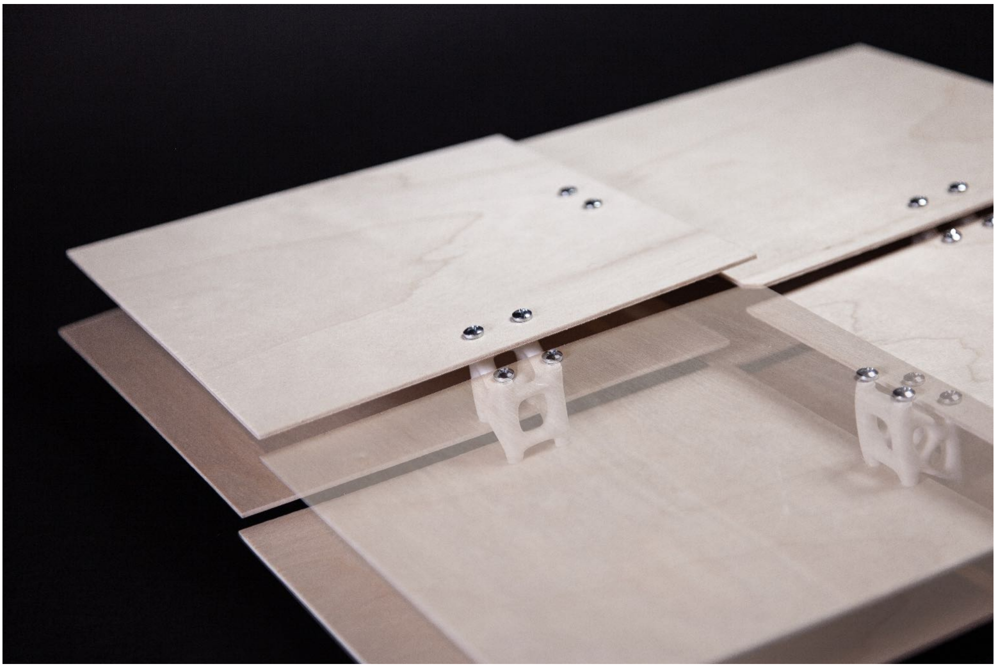

Figure 11: Scale prototype with FDM printed connectors.

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